Quantum Mechanics, Real and Artificial Intelligence*

H. S. Green[A] *and T. Triffet*[B]

[A] Department of Physics and Mathematical Physics,
University of Adelaide, Adelaide, S.A. 5001, Australia.
[B] NASA/UA Space Engineering Research Center,
University of Arizona, Tucson, AZ 85712, U.S.A.

Abstract

Some incompletely resolved problems in the quantal theories of measurement and observation are discussed with reference to Schrödinger's 'cat paradox' and the paradox of Wigner's friend. A simple version of the theory of measurement is presented, which does not completely resolve these paradoxes but suggests the need for an objective quantal description of the process of observation, and the formation of memory, of an event originating at the microscopic level, by an animal or artificial intelligence. A quantised model is then developed to simulate the function of the cerebral cortex in the formation of memory of sensory impressions, with macroscopic observables expressed in terms of parafermion operators of very large order. A letter from Schrödinger, which corrects some published versions of his paradox, is presented as well as a short account of the simulated formation of long-term memory by the model in an appendix.

1. Introduction

Quantum mechanics as an exact science is just 64 years old, and for more than half of this period significant contributions to it have been appearing regularly under the name of I. E. McCarthy; there is not one of these which has not pushed back the frontiers of knowledge in some direction, but the first (McCarthy 1955) was on an application of generalised quantum statistics and this will also be an incidental feature of the present paper.

We shall also be concerned with a fundamental problem which first presented itself to one of the authors (H.S.G.) during his acquaintance in Dublin with Erwin Schrödinger, only a year before his first meeting with Ian McCarthy. This is essentially the problem of measurement and observation, but was formulated by Schrödinger as a paradox involving a cat: the cat is constrained in such a way that it will be killed if a Geiger counter registers an event at the quantal level in a specified period of time. The details of this thought experiment are described in a letter which is reproduced in Fig. 1. According to one version of the Copenhagen interpretation of quantum mechanics (never endorsed by Bohr, Born, Jordan or Heisenberg), at the end of the experiment the cat is represented by a superposition of two kinds of wavefunction, the first corresponding to live states and the second to states in which the cat is

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* Dedicated to Professor Ian McCarthy on the occasion of his sixtieth birthday.

dead. When the result of the experiment is noted by a conscious observer, one kind of wavefunction is suddenly eliminated. Schrödinger's letter refers to a paper (Green 1958) which attempted to model an experiment of this type, and tended to vindicate a somewhat different 'orthodox' version of the Copenhagen interpretation of quantum mechaincs. However, it is evident that it did not affect Schrödinger's objections to this interpretation at all; he believed that a single wavefunction should be adequate to describe any experiment, including the processes of measurement and observation.

Schrödinger was by no means alone in his heterodox views on the deterministic nature of quantum mechanics, and later Wigner (1962) proposed a new paradox, the paradox of Wigner's friend, who played the role of Schrödinger's cat in detecting the occurrence or non-occurrence of an event at the quantal level and registering this in his own mind, though not yet in Wigner's. On the basis of this paradox, Wigner suggested that the brain must be subject to laws different from those of inanimate matter. The authors of the present paper have not been able to accept this and, partly to clarify the issues involved, have developed increasingly realistic models, including quantal models, of the brain (Triffet and Green 1975, 1989; Green and Triffet 1975, 1989).

Like Schrödinger (1967), we recognise a distinction between measurement and observation: the former requires only inanimate measuring devices, but the second requires intelligent though not necessarily human or other animal intervention. In recent years there has been renewed interest in von Neumann's (1966) concept of artificial life (see Langton 1986, 1989), of machines which might display most of the outward characteristics of living matter, including reproduction, in a favourable environment. However, in spite of the rapid development in the last decade of different kinds of computers and associated software, including 'computer viruses', there is one respect in which existing machines fail completely to mimic the action of the animal brain: in their power to make intelligent decisions, the outcome of which cannot be predicted, even in principle. They lack precisely the sort of uncertainty that most physicists associate with quantal phenomena. It has been concluded by distinguished physicists (e.g. Bohr 1933; Jordan 1941) and neurophysiologists (e.g. Eccles 1953) alike that, in view of evidence that the nervous system is sensitive to external interactions as weak as a few quanta, it is reasonable to suppose that it may also be affected by internal interactions of a similar type. If this is granted, the appearance of consciousness, and the ability to make decisions unfettered by inherited or environmental influence, could be attributed to an escalation of events initiated at the quantal level. In this sense, a cloud chamber or a Geiger counter could be regarded as a more promising component of an artificial intelligence than a computer chip or floppy disk.

There is today a rapid growth in areas of science concerned with narrowing the gap between artificial and animal intelligence (see Rumelhart and McClelland 1987). There is no reason to believe that this separation can never be eliminated: as de Chardin (1959) has pointed out, the mere existence of intelligence implies at least the potential of intelligence in ordinary matter. It is already possible to construct artificial neural networks which perform complex parallel processing, and artificial brain components such as synapses; but these clearly lack some important element. The introduction of quantal phenomena in this

context could play a vital part in what might be regarded as the ultimate crucial step in the process of evolution.

2. The Theory of Measurement

Today, quantum mechanics, insofar as it is a widely accepted discipline of physics, is a mixture of a deterministic dynamical theory and an indeterministic theory of measurement still in much the same state as it was formulated by Born (1926). There is no reason to question the applicability of the deterministic theory of the wavefunction or state vector to what are known as pure states of a microscopic system, though it should be recognised that such states represent an idealisation never perfectly realised, and persist only as long as the system is isolated from all other matter, including macroscopic measuring devices and observers. The status of the theory of measurement and observation is less satisfactory; von Neumann's (1955) exposition has met with much well-founded criticism, but has not yet been displaced by anything as simple and elegant, in spite of a wide variety of contributions to the subject (Everett III 1957; Green 1958; Elsasser 1958; Yanase 1961; Daneri *et al.* 1962; Wigner 1963; Jauch 1964; Bell 1966; Lamb 1969; De Witt 1970; Bass 1971; see also Tarozzi and Van der Merwe 1988). In this sense, Einstein's characterisation of quantum mechanics as an incomplete theory (Einstein *et al.* 1935) is justified.

There is some consensus in the literature referred to above that there is a serious difficulty if concepts such as pure state, wavefunction and state vector are extended to macroscopic measuring devices and observers; this difficulty, from one point of view, stems from the fact that measurement and observation both involve irreversible processes, which cannot be adequately described in terms of such concepts. Quantal theories of irreversible processes (Born and Green 1947; Mori 1956; Kubo *et al.* 1957) make use of a generalisation of the theory of the density matrix or statistical operator, as formulated by von Neumann (1955). From another point of view, the processes of measurement and observation require the transfer of information, as defined in the quantal context by Brillouin (1964), again using the generalised density matrix. The relevance of a quantal model of cortical action to Schrödinger's cat paradox and the paradox of Wigner's friend becomes apparent if it can be shown that the information content of the cat's brain or the friend's brain is neither indeterminate nor subjective, but is stored in their long-term memories, which can be accessed by an appropriate stimulus. Moreover, a sufficiently realistic model may reveal how to develop an artificial intelligence which, at least in this respect, could perform the same functions as an animate brain. These are the principal objectives of the present paper.

We suggest that, to resolve the paradoxes, the theory of measurement, concerned with the interaction of a microscopic system and a macroscopic measuring device, should be complemented by a theory of observation, concerned with the transfer of information on the result of the measurement to an intelligent observer. In the next section, we shall consider the process of observation in the light of a simple but realistic quantal model of the cortex at the ionic level, parallel to the classical model recently developed (Green and Triffet 1989; Triffet and Green 1989), and differing from our original quantal

19th June 1958

Dear Green,

Many thanks for your letter of 7th May including a copy of your paper. Excuse this belated answer. I was laid up for many weeks, partly in hospital, with a bad attack of thrombo-phlebitis (inflammation of a vein in the left leg) and did not feel like writing or doing physics.

I wonder who it was that first distorted my so-called 'cat-paradox' in the way I now find it quoted by everybody who mentions it, which met with very justified criticism by Pryce at the Ninth Symposium at Bristol. I did not venture to 'take a photon' and launch it towards a half-silvered mirror; I took a tiny speck of radioactive substance, say an α-radiator, and placed it in the centre of a hollow sphere of lead with only a tiny opening. It is easy to take the amount of α-radiator and the solid angle of the opening in a fashion, that only one α-particle will, on the average, pass through the opening within half an hour or an hour. This may then trigger a Geiger counter etc. etc.

I have no doubt that your paper, which vindicates the orthodox view*, is quite correct. Since I am very far from accepting the orthodox view, I beg to be excused for not being very enthusiastic about this vindication.

We are about to leave for Alpbach early in July. I do not think we shall be in the Austrian Tirol in October. It is at that time pretty cold there.

Very sincerely yours,

E. Schrödinger

* in a particular point

Fig. 1. Schrödinger's authoritative version of his 'cat' paradox.

model (Triffet and Green 1975) by its use of a different type of quantum statistics. But as the theory of measurement is also in question, we first state in very simple terms a generalisation of an argument (Green 1958) which, as Fig. 1 shows, Schrödinger was prepared to accept.

We denote by ρ the density matrix of a system consisting of the microscopic system S and the macroscopic measuring device or detector D which, as in the paradoxes of Schrödinger and Wigner, may include the intelligent observer. At time $t = 0$, S and D have not yet had the opportunity to interact, and ρ can be expressed as the direct product $\rho_S \rho \rho_D$ of their separate density matrices. If S has been prepared so that it is in a pure state, ρ_S is a minimal projection matrix independent of the time, satisfying

$$\rho_S^2 = \rho_S, \qquad \text{tr}_S(\rho_S) = 1, \tag{1}$$

where tr_S is the trace of the matrix representing S in isolation. For the reasons given above, the density matrix of D cannot be assumed to be of the same type, but may be expressed in the form

$$\rho_D = \sum_i p_i \rho_{Di}, \tag{2}$$

in which the ρ_{Di} are projection matrices satisfying relations like (1), and the p_i can be interpreted as probabilities; the information, or defect of entropy of D, is given by

$$I = k \sum_i p_i \log(N p_i), \tag{3}$$

where N is the number of values of i, and will be assumed to be very large but not infinite. If, instead of $k = 1/\ell n(2)$, which yields information in bits, we take k to be Boltzmann's constant, then (3) defines the defect of entropy. Thus the gain of information due to an increase δN_α in the number of particles of type α is $\mu_\alpha \delta N_\alpha / T$, where μ_α is the chemical potential per particle and T is the absolute temperature.

We suppose there is a possibility, but no certainty, that S and D interact following the initial time, and denote the potential of the interaction in the interaction representation by $V_D(t) \rho_{S+}$, where $V_D(t)$ depends only on the dynamical variables of D, and ρ_{S+} is a projection matrix which does not commute with ρ_S, though it acts in the same vector space. The density matrix of the composite system at time t is given by

$$\rho(t) = \exp[-i\, U_D(t) \rho_{S+}] \rho_S \rho_D \exp[i\, U_D(t) \rho_{S+}],$$

$$U_D(t) = \hbar^{-1} \int_0^t V_D(t)\, \mathrm{d}t. \tag{4}$$

The reduced density matrix for S is found by taking the trace of this matrix in the space of the dynamical variables of D:

$$\text{tr}_D[\rho(t)] = P_+ \rho_{S+} + P_- \rho_{S-} + P_{+-} \rho_{+-} + P_{-+} \rho_{-+}. \tag{5}$$

Here $\rho_{S-} = 1 - \rho_{S+}$, $\rho_{+-} = \rho_{S+}\rho_S\rho_{S-}$, and $\rho_{-+} = \rho_{S-}\rho_S\rho_{S+}$ are components of ρ_S, of which the first represents the possibility that S has not interacted with D, and the last two represent the possibility that it remains indeterminate whether the interaction has occurred or not. The coefficients P_+ and P_-, defined by $P_+\rho_{S+} = \rho_{S+}\rho_S\rho_{S+}$ and $P_-\rho_{S-} = \rho_{S-}\rho_S\rho_{S-}$, may be interpreted as probabilities that the interaction does or does not occur. In a partial resolution of the paradoxes, it should be shown that these are in effect the only possibilities.

It is thus required to show that, under appropriate conditions, the coefficients P_{+-} and P_{-+} of the last two components in (5) are negligible soon after the interaction begins. In fact we have

$$P_{+-} = \text{tr}_D[\exp(-i\,U_D(t)\rho_D)], \qquad (6)$$

and it is easy to see that, since the eigenvalues of $U_D(t)$ are real, this has a limiting value whose real part can never exceed its initial value of 1. To go further, it is necessary to use the fact that D is a macroscopic device with a very large number of degrees of freedom. If, as in the next section, the degrees of freedom can be chosen so that they are, to a considerable extent, dynamically independent of one another, the above expression resolves into the product of a large number of factors:

$$P_{+-} = \prod_n \text{tr}_{Dn}[\exp(-i\,U_{Dn}(t)\rho_{Dn})], \qquad (7)$$

almost all of which tend to values that are less than 1. Clearly such an expression becomes negligible soon after the interaction begins. Thus, under suitable conditions, the reduced density matrix for S alone soon approaches a form representing an impure state with the probabilities P_+ and P_- for interaction or no interaction with the measuring device.

Of course, not all macroscopic objects are efficient measuring devices, since it may be very difficult to determine from them, by inspection or otherwise, whether the interaction has actually occurred. Most efficient detectors of microscopic events are in a state of low entropy, such as a metastable state, and the interaction is sufficient to induce a large transfer of entropy and information which is easily detected by an intelligent observer at the macroscopic level. The model to be developed in the next section suggests that the intelligent observer may also be classified in this way, so that there is no essential difference, in that respect, between an efficient inanimate measuring device and the observer who takes note of the measurement. In this sense, the measuring device has one essential attribute of an artificial intelligence.

3. A Quantal Theory of Cortical Function

We now take up the suggestion that the resolution of the quantum-mechanical paradoxes such as Schrödinger's and Wigner's could depend in part on a quantal theory of observation which gives an objective significance to the transfer of sensory information concerning a microphysical measurement to the animal

cortex. This will be done with the help of a simple but quite realistic quantal model of the cortex.

Let us consider the system of neurons of the sensory and sensory association cortex and the hippocampus which are known to be active in the formation of the memory of a sensory event. There is evidence (see Seifert 1983) that the long-term memory does not reside in the hippocampus, which, however, receives and returns information from many parts of the cortex, including the sensory association cortex (Witter *et al.* 1989); in the process, it synchronises the transfer of information with its own theta-rhythm (Carpenter 1982), and thereby imparts a sequence to different memories (see the Appendix). Any neuron of the system considered may interact with another at a synapse, where its axon is in close relation to a dendrite or the cell body of the other. We have presented a classical model of this system elsewhere (Green and Triffet 1989); for the present purpose it is necessary to develop the quantal generalisation only far enough to allow the application of the theory of the last section. We shall first introduce a set of quantal observables and operators, corresponding not only to the neurons of the system but also to their synapses.

A quantised activation variable N_j will be introduced for the jth neuron; for the sake of simplicity in the present context this is expressed as the difference between just two observables A_j and B_j, whose eigenvalues a and b in a particular state are conceived as the numbers of sodium and potassium ions in the cell, in excess of certain minimum values, so that they have non-negative integral values in the range $(0, p)$. Then N_j has an integral eigenvalue $n = a - b$ in the range $(-p, p)$. In classical theories, it is a rough nonlinear measure of the potential at the axon hillock of the cell. In some neural network theories (Rumelhart and McClelland 1987), n has only the values 0 and 1, and in our classical model referred to above the number of activation levels is still only of the order of 10; but in the present context it must of course be many orders of magnitude larger.

If ρ_{jn} is the projection matrix for the nth eigenvalue, the activation variable and the associated energy H_j of the neuron (when nonlinear effects are neglected) are given by

$$N_j = \sum_n n\rho_{jn}, \qquad H_j = \mu N_j, \tag{8}$$

where μ is half the difference in chemical potential between the sodium and potassium ions. The activation variable, like other quantal observables taking large but finite values, is both conveniently and appropriately expressed in terms of creation and annihilation operators a_j^*, b_j^* and a_j, b_j of parafermi statistics, a type of generalised quantum statistics, of very large order p (Green 1953; McCarthy 1955); thus

$$N_j = A_j - B_j = \tfrac{1}{2}([a_j, a_j^*] - [b_j, b_j^*]), \tag{9}$$

since this has eigenvalues spanning the range $(-p, p)$. The projections in (9) are connected by relations such as $a_j^* \rho_{jn} a_j = (p - a)\rho_{jn+1}$ $(0 \leq a \leq p)$, $a_j \rho_{jn} a_j^* = a\rho_{jn-1}$. However, we shall use only projections and commutators;

the latter satisfy the same commutation rules as if they were constructed from ordinary fermion operators.

An activation level is classified as refractory ($n = -p, -p+1, ..., r-1$), resting ($n = r, r+1, ..., t-1$), or firing ($n = t, t+1, ..., p$), where $r = 0$ is the lowest resting level and t is the firing threshold. In any resting level, the neuron may be activated, as a result of synaptic input from the kth neuron; then its activation level is changed by an integer w_{jk} known as the weight of the synapse. The macroscopic effect of the weight is to raise or lower the potential of the post-synaptic neuron, but in the present microscopic context we may regard the weight as a measure of the number of calcium ions participating in synaptic transmission (Katz and Miledi 1967). Synaptic input may be excitatory ($w_{jk} > 0$) or inhibitory ($w_{jk} < 0$), depending on the type of the kth neuron forming the synapse. We introduce an observable W_{jk} whose eigenvalue is w_{jk} in this state of the synapse and its associated neurons; this implies that the weight is to be regarded as a dynamical variable.

As the result of excitation, a neuron may be left in a resting level n above the lowest resting level r, and is then said to be potentiated, with potentiation $n - r$; such potentiation may last for many hours. It is known (Bliss and Lomo 1973; Fifkova and Anderson 1981) that activation and long-term potentiation result in synaptic growth and the sensitisation of the synapse responsible for the activation, so that the weight w_{jk} of the synapse increases in magnitude. This change persists even after the potentiation ceases, and it is now generally accepted (Eccles 1984) that such processes are fundamental in the formation of memory. We may assume a spectral decomposition of the observable W_{jk} similar to that of N_j in (8):

$$W_{jk} = \sum_w w \rho_{jkw}, \tag{10}$$

in which $|w|$ takes integral values in the range $(1, w_m)$, limited by some maximum value w_m depending on the number of calcium ions which can be made available at the synapse. We shall define ρ_{jkw} so that it has the eigenvalue 1 when the kth neuron is in a firing state and the jth neuron is in a resting state, and has the eigenvalue 0 otherwise.

In addition to synaptic activation, a neuron may receive alternating excitatory and inhibitory activation from the extracellular field. Because of the balance of excitatory and inhibitory synaptic activation received by the great majority of neurons, they will reach a firing level only when the extracellular activation is excitatory, so that firings are normally synchronous with maxima of rhythmic variations of the field. Shortly after firing, the activation level reaches its highest value and declines rather rapidly to a minimum in the refractory range, after which it slowly increases again until it reaches the lowest resting value. During this entire phase of firing and recovery, which normally lasts for about $0 \cdot 1$ s, the neuron is insensitive to synaptic stimuli. The progress of the cell through the refractory states may in fact be regarded as an essential part of the firing process. In the history of a cell, its activation level undergoes a series of cycles of successive potentiation and firing; though these changes are not strictly periodic, they are approximately reversible. But, due to the

sensitisation of synapses in the potentiated states, the synaptic weights are also changed and such changes are irreversible.

We consider first the reversible changes in activation level which result mainly from changes in the number of potassium ions: the extracellular activation is in this category, and so are the later parts of the firing phase. For our present purpose it is unnecessary to distinguish between these, and it will be supposed simply that they contribute the terms

$$H'_j = \tfrac{1}{2}\lambda[c_j, c_j^*] + \tfrac{1}{2}\nu([b_j, c_j^*] + [c_j, b_j^*]) \tag{11}$$

to the energy of the jth neuron, the first term representing the extracellular source and the second the interaction. For c_j^* and c_j we may again use parafermion creation and annihilation operators of the very large order p. In the Heisenberg representation, any operator O_j for the jth neuron varies with time like

$$i\hbar dO_j/dt = [O_j, H_j + H'_j], \tag{12}$$

and it follows from (9) and (11) that H_j satisfies the differential equation

$$\hbar^2 d^3 H_j/dt^3 + \nu^2 dH_j/dt = 0. \tag{13}$$

Thus, as a consequence of extracellular activation alone, the quantal activation variable of the neuron, and also its expectation value, will undergo periodic variations of angular frequency $\nu/\hbar$; this was also a feature of the classical model.

Finally we consider synaptic activation, and the early phase of the firing process which is characterised by a rapid flux of sodium ions from extracellular sources into the cell, triggered by calcium currents originating in particular at synapses on the cell membrane. This is responsible for the contribution

$$V_j = \sum_k V_{jk} = \tfrac{1}{2} \sum_k ([a_j, c_j^*]W_{jk} + W_{jk}[c_j, a_j^*]) \tag{14}$$

to the energy of the jth neuron. Of course only those neurons making synapses on this neuron need be included in the summation. We note that W_{jk} may be expressed in the form $w_{jk}\rho_{jr}\rho_{k+}$, where ρ_{jr} is the projection onto the resting states of the jth neuron, and ρ_{k+} is the projection onto the firing states of the kth neuron. The addition of (14) to (11) implies changes in the activation energy similar to those resulting from the extracellular field, but such changes, though more rapid, are limited to the relatively small range of resting states and occur only if one of the neurons synapsing onto the jth neuron fires. It is also an interesting feature of the present model that the quantal weights may change with time; if we substitute W_{jk} for O_j in (14), we obtain a non-vanishing expectation value for dW_{jk}/dt in general, proportional to w_{jk}, though the expectation value vanishes in the lowest resting state of the jth neuron. The stochastic variation of the synaptic weights is an essential part of the process of memory formation which merits further study.

We now observe that in the interaction representation the interaction energy V_{jk} defined above has a form $V_{jD}\rho_{k+}$, similar to that $(V_D\rho_+)$ assumed in the elementary theory of measurement given at the end of the last section. We may thus expect to express the density matrix ρ_k of the kth neuron as a sum of just two numerically significant terms ρ_{k+} and ρ_{k-} representing the possibilities that this neuron does or does not fire. The implication here is that, under suitable conditions, the jth neuron may be regarded as an efficient detector for the firing of the kth neuron. The essential condition in the present context is that the synapse responsible for the firing suffers an objective irreversible change at the microscopic level, and this could clearly happen if the synaptic weight is changed sufficiently as a result of long-term potentiation. The objectivity of such changes in nature is in fact guaranteed by the possibility of experimental observation (Fifkova and Anderson 1981) of synaptic growth.

References

Bass, L. (1971). *Hermathena* **112**, 52–68.

Bell, J. (1966). *Rev. Mod. Phys.* **38**, 447–52.

Bliss, T., and Lomo, T. (1973). *J. Physiol. (London)* **232**, 331–56.

Bohr, N. (1933). *Nature* **131**, 421–3; 457–9.

Born, M. (1926). *Z. Phys.* **37**, 862–7; **38**, 803–27.

Born, M., and Green, H. S. (1947). *Proc. R. Soc. (London)* A **191**, 168–81.

Brillouin, L. (1964). 'Scientific Uncertainty and Information' (Academic: New York).

Carpenter, D. O. (1982). 'Cellular Pacemakers' (Wiley: New York).

Daneri, A., Loinger, A., and Prosperi, G. H. (1962). *Nucl. Phys.* **33**, 297–319.

de Chardin, P. T. (1959). 'The Phenomenon of Man' (Harper: New York).

De Witt, B. (1970). *Phys. Today* **23**, 155–65.

Eccles, J. C. (1953). 'The Neurophysiological Basis of Mind', Ch. 8 (Clarendon: Oxford).

Eccles, J. (1984). *In* 'Cerebral Cortex', Vol. 2 (Eds E. G. Jones and A. Peters), pp. 1–36 (Plenum: New York).

Einstein, A., Podolsky, B., and Rosen, N. (1935). *Phys. Rev.* **47**, 777–80.

Elsasser, W. M. (1958). 'The Physical Foundation of Biology' (Pergamon: New York).

Everett, H. III (1957). *Rev. Mod. Phys.* **29**, 454–65.

Fifkova, E., and Anderson, J. A. (1981). *Exp. Neurol.* **74**, 621–7.

Green, H. S. (1953). *Phys. Rev.* **90**, 270–3.

Green, H. S. (1958). *Nuovo Cimento* **9**, 880–9.

Green, H. S., and Triffet, T. (1975). *Int. J. Quant. Chem., Quant. Biol. Symp.* **2**, 289–96.

Green, H. S., and Triffet, T. (1989). *Math. Comput. Modelling* **12**, 673–94.

Jauch, J. M. (1964). *Helv. Phys. Acta* **37**, 293–316.

Jordan, P. (1941). 'Die Physik und das Geheimnis des Organischen Lebens' (F. Vieweg: Braunschweig).

Katz, B., and Miledi, R. (1967). *J. Physiol.* **189**, 535–44.

Kubo, R., Yokota, M., and Nakajima, S. (1957). *J. Phys. Soc. Jpn* **12**, 1203–11.

Lamb, W. E. (1969). *Phys. Today* **22**, 23–9.

Langton, C. G. (1986). *Physica* D **22**, 120–49.

Langton, C. G. (Ed.) (1989). 'Artificial Life' (Addison–Wesley: Redwood City, Ca.).

McCarthy, I. E. (1955). *Proc. Camb. Phil. Soc.* **51**, 131–40.

Mori, H. (1956). *J. Phys. Soc. Jpn* **11**, 1029–44.

Rumelhart, D. E., and McClelland, J. L. (1987). 'Parallel Distributed Processing' (MIT Press: Cambridge, Mass.).

Schrödinger, E. (1967). 'What is Life? Mind and Matter' (Cambridge Univ. Press).

Seifert, W. (Ed.) (1983). 'Neurobiology of the Hippocampus' (Academic: New York).

Tarozzi, G., and Van der Merwe (1988). 'The Nature of Quantum Paradoxes' (Kluwer Academic: Dordrecht).

Triffet, T., and Green, H. S. (1975). *J. Biol. Phys.* **3**, 53–76; 77–93.
Triffet, T., and Green, H. S. (1989). *J. Theor. Biol.* **136**, 87–116.
von Neumann, J. (1955). 'The Mathematical Foundations of Quantum Mechanics' (Princeton Univ. Press).
von Neumann, J. (1966). *In* 'Theory of Self-Reproducing Automata' (Ed. A. W. Burks) (Univ. Illinois Press).
Wigner, E. P. (1962). *In* 'The Scientist Speculates' (Ed. I. J. Good), pp. 284–302 (Heinemann: London).
Wigner, E. P. (1963). *Am. J. Phys.* **37**, 6–15.
Witter, M. P., Groenewegen, H. J., Lopes da Silva, F. H., and Lohman, A. H. M. (1989). *Prog. Neurobiol.* **33**, 161–253.
Yanase, M. M. (1961). *Phys. Rev.* **123**, 666–8.

Appendix: A Model of Memory Formation

We conclude with a brief account of the operation of a model for the simulated formation of memory of a particular sensory impression I_1, which could result from an event at the microphysical level. The computer simulation can be carried out with little modification of the program listed in conjunction with the corresponding classical model (Green and Triffet 1989).

One essential feature which distinguishes the record of the microphysical event made by an intelligence from that of a simple detector is that it forms part of a temporal sequence of records which gives it context and meaning. We should not, therefore, consider the impression I_1 in isolation, but as an element of a sequence $I_0, I_1, I_2, \ldots$.

The neurons of the model intelligence are numbered in the temporal order in which they could respond to the sequence of sensory impressions. They belong to a sequence of units, each containing several neurons, which we shall denote by R_i, S_i and H_i ($i = 0, 1, 2, \ldots$) in correspondence with the elements I_i. The first neuron capable of detecting the particular sensory impression I_1 of the sequence must belong to the sensory receptor unit R_1, and either fires and so detects the microphysical event, or does not fire. If it fires, the output from R_1 is relayed to a set of sensory association units, some of which may be supposed to be already sensitised and activated as a result of the immediately preceding sensory impression I_0; only one of these sensory units (S_1) need be represented in the model. If the event is detected, several neurons, including the pyramidal cell of S_1 will fire and, in consequence, a new set of already sensitised units of the sensory cortex, including S_2, will be activated from two sources (S_1 and I_2) and fire. The independent activation and firing of $S_0, S_1, S_2, \ldots$ may be repeated subsequently as the result of ongoing conscious or unconscious activity and this repetition constitutes the short-term memory of the sensory impressions.

However, as another consequence of the initial firing of S_1, a set of hippocampal units, including H_1, will be potentiated; these are selected by their simultaneous activation by the theta-rhythm. Subsequent repeated firings of S_1 may result in further potentiation of H_1, but only if the firings are synchronous with the theta-rhythm. The long-term potentiation of granule cells of H_1 sensitises the unit, so that it will ultimately fire and contribute to the activation of S_2, which must then also be synchronous with the theta-rhythm. Thus, with the participation of hippocampal units, the activation and firing

of S_0 is necessarily followed by the sequential firing of $H_0, S_1, H_1, S_2, H_2, \ldots$. At this stage, medium-term memory of the sequence of impressions has been formed. Finally, as a result of sensitisation of the synapses from S_0 onto S_1, from S_1 onto $S_2, \ldots$, the sequential firing of $S_0, S_1, \ldots$ is possible without the participation of the hippocampal units; at this stage, empirically a few days after the sensory experience, long-term memory of the experience has been established.